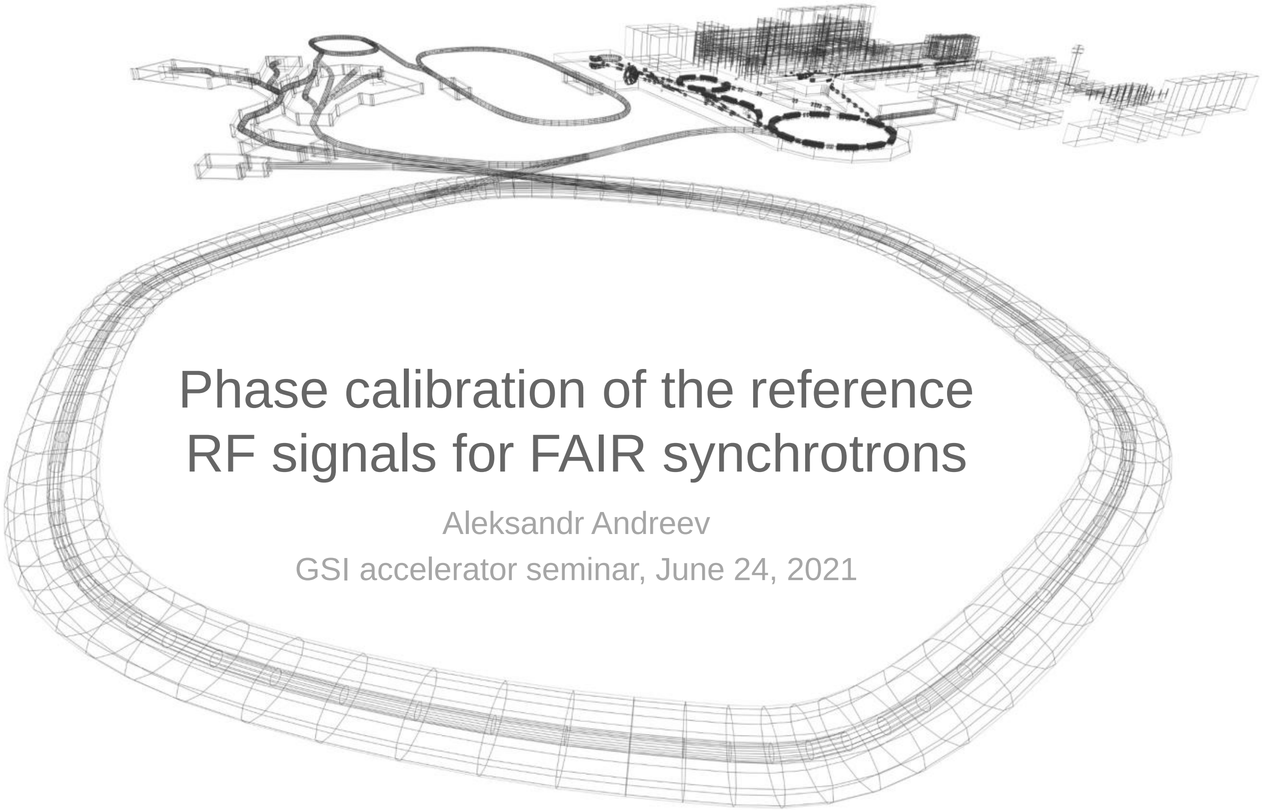


Phase calibration of the reference RF signals for FAIR synchrotrons

Aleksandr Andreev

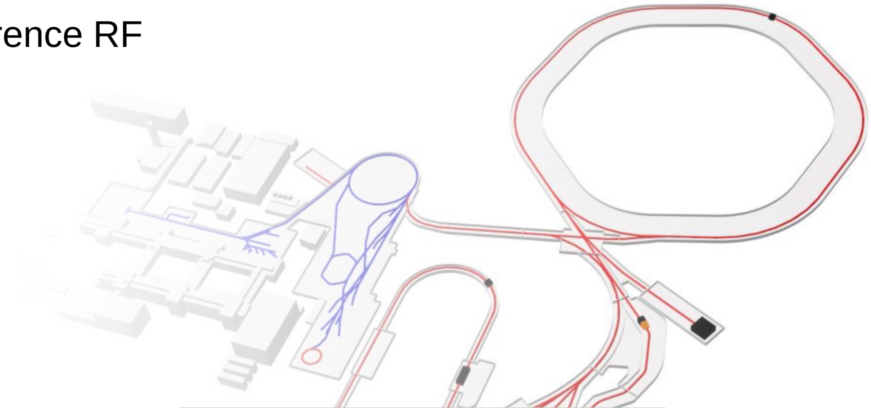
GSI accelerator seminar, June 24, 2021

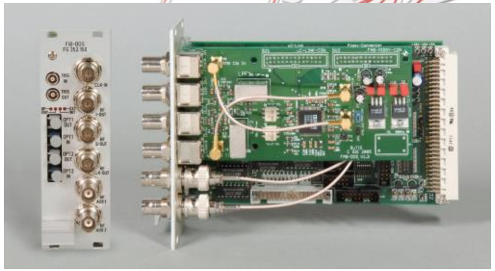
Outline

- Introduction and description of the problem
- Requirements for the calibration procedure
- Description of the developed method
- Convergence study and numerical optimization
- Uncertainty analysis of the method
- Application at SIS18 supply area
- Stability and environmental influences analysis

Introduction I

- Large circumference of the SIS100 and reference RF signals
- 8 RF supply areas distributed along the ring
- Direct Digital Synthesis (DDS) modules generate reference RF signals

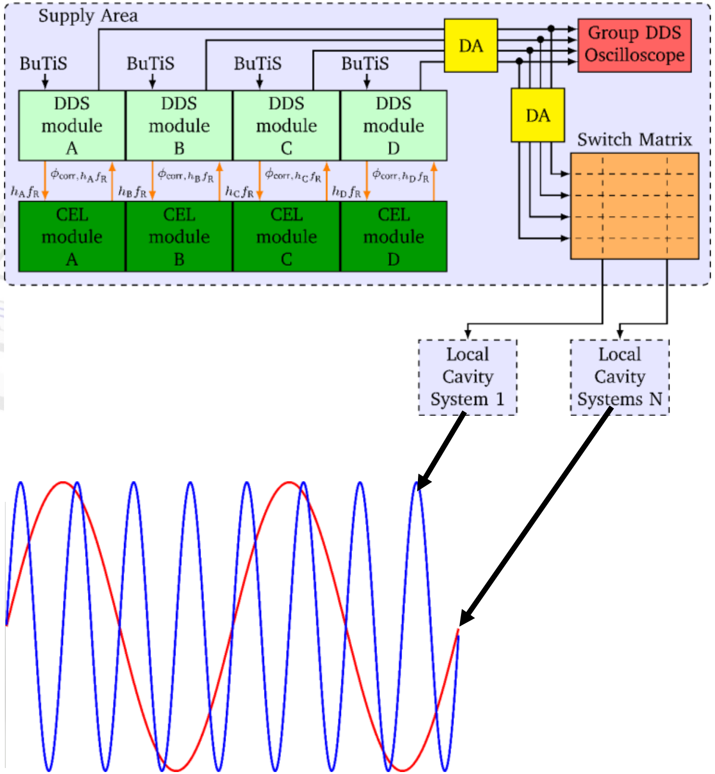




Introduction II

- Large circumference of the SIS100 and reference RF signals
- 8 RF supply areas distributed along the ring
- Direct Digital Synthesis (DDS) modules generate reference RF signals

- 4 DDS modules mounted in one crate: multiharmonic operations
- Time synchronization: Bunch Phase Timing System (BuTiS)
- Revolution frequency ramp: Cental Control System (CCS)
- Switch Matrix routes Group DDS signals to local cavity systems

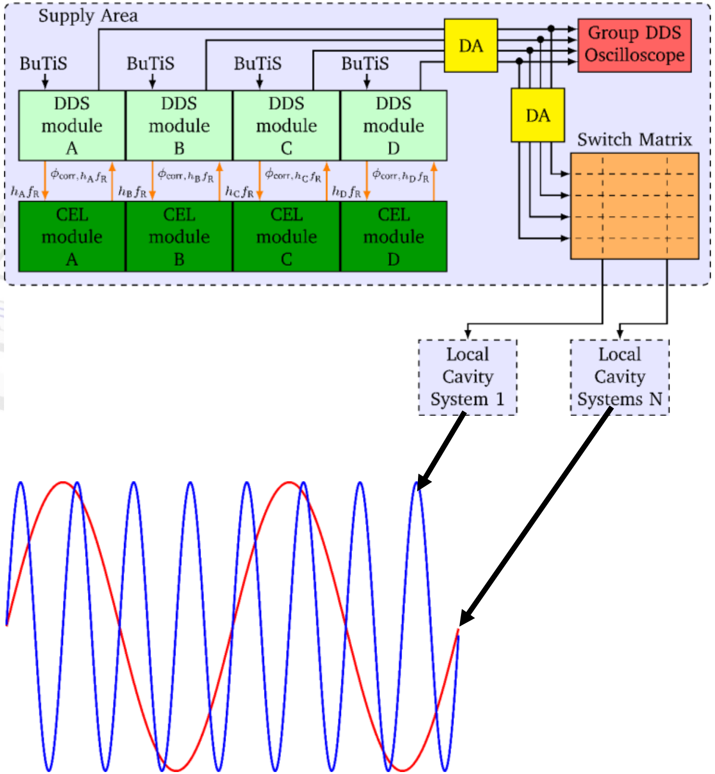


Introduction III

- Large circumference of the SIS100 and reference RF signals
- 8 RF supply areas distributed along the ring
- Direct Digital Synthesis (DDS) modules generate reference RF signals

- 4 DDS modules mounted in one crate: multiharmonic operations
- Time synchronization: Bunch Phase Timing System (BuTiS)
- Revolution frequency ramp: Cental Control System (CCS)
- Switch Matrix routes Group DDS signals to local cavity systems

- Output stage: undesired phase deviations ➔ reference signals ➔ local cavity systems
- Calibration needed to reach the desired beam quality requirements



Requirements

- Phase accuracy of the reference RF signals better than ±1°
- A method has to:
  - Reduce number of possible combinations
  - Calibrate of all the modules in the same way
  - Calibrate independent of harmonic number in operation
- Calibration during maintenance periods
- Long term stability: decrease time for maintenance
- Automatic system integrated into the existing control environment

➔ Absolute phase calibration method based on sine wave fitting algorithms

Sine wave fitting algorithms (SFA) I

- Advantages: high accuracy, robustness for noncoherent sampling, simplicity of implementation
- Sampled signal: a sequence of samples y_n taken at time instants $t_n, n \in [1, \dots, N]$
- A set of unknown parameters $\mathbf{x} = (\tilde{V}, \phi, C, \omega)^T$ characterizes its waveform

$$v(t_n) = A\cos(\omega t_n) + B\sin(\omega t_n) + C$$

where $A = \tilde{V}\sin\phi$, $B = \tilde{V}\cos\phi$ and $\phi = \mathrm{atan2}\,(A, B)$

- Including higher harmonics:

$$\begin{aligned} v(t_n) &= C + \sum_{h=1}^{h_{\text{fit max}}} \tilde{V}_h \sin(h\omega t_n + \phi_h) \\ &= C + \sum_{h=1}^{h_{\text{fit max}}} \left(A_h\cos(h\omega t_n) + B_h\sin(h\omega t_n)\right) \end{aligned}$$

- Estimate the unknown parameters $\hat{\mathbf{x}}$ that minimize

$$\sum_{n=1}^{N} (y_n - v(t_n))^2$$

Sine wave fitting algorithms (SFA) II

- Phase of harmonic h:

$$\phi_{h,f} = \mathrm{atan2}\left(A_h, B_h\right)$$

- Parameters of $h_{\text{fit max}}$ harmonics can be estimated
- Phase of the fundamental component $\phi_{1,f}$ is relevant
- Three- and four parameter algorithm for known and unknown frequency, respectively

Calculation of the phase correction

- BuTiS T_0 signal as a reference
- For ideal (i.e. no phase deviations) signal:

$$\phi_f - \phi_{\mathrm{init}} = 2\pi f_{\mathrm{DDS\ RF}} \left(N_{\mathrm{ref}} T_{\mathrm{ref}} - \tau_\delta\right)$$

- Real signal with $\phi_{\mathrm{e},f}$:

$$\phi_{\mathrm{meas},f} - \phi_{\mathrm{init}} = 2\pi f_{\mathrm{DDS\ RF}} \left(N_{\mathrm{ref}} T_{\mathrm{ref}} - \tau_\delta\right) + \phi_{\mathrm{e},f}$$

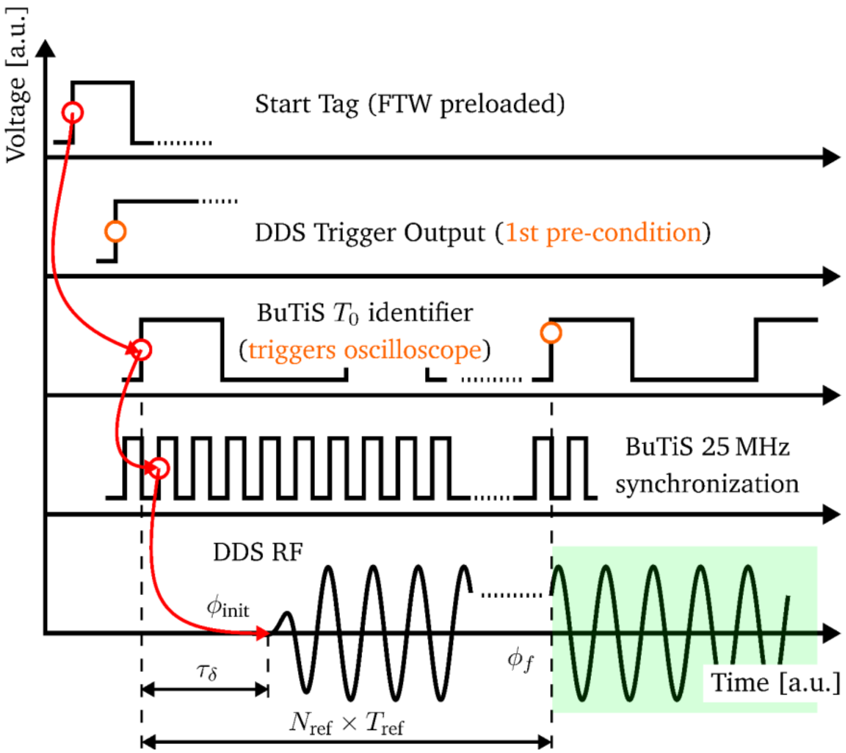
- To eliminate $\phi_{\mathrm{e},f}$ modify initial phase that:

$$\phi_f - \phi_{\mathrm{init,\ new}} = 2\pi f_{\mathrm{DDS\ RF}} \left(N_{\mathrm{ref}} T_{\mathrm{ref}} - \tau_\delta\right) + \phi_{\mathrm{e},f}$$

- Phase error and phase correction:

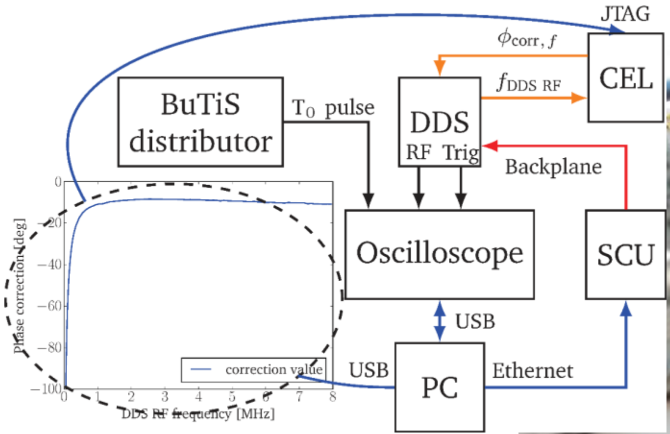
$$\phi_{\mathrm{e},f} = \phi_{\mathrm{meas},f} - 2\pi f_{\mathrm{DDS\ RF}} \left(N_{\mathrm{ref}} T_{\mathrm{ref}} - \tau_\delta\right)$$

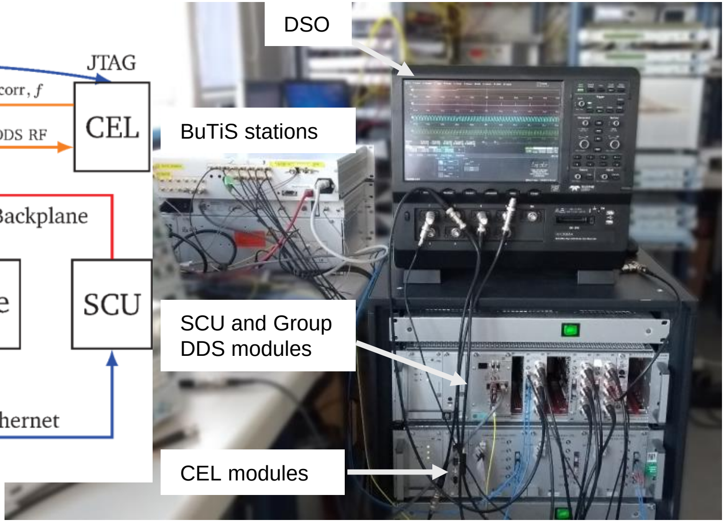
$$\phi_{\mathrm{corr},f} = \pi - \left[\left(-\phi_{\mathrm{e},f} + \pi\right) \bmod 2\pi\right]$$



Measurement setup and procedure

- Calibration PC
- Front end controller: SCU
- DDS modules
- BuTiS stations:
  - Reference signal generator
  - Clock distribution amplifier
- DSO for data sampling and transferring
- CEL modules





- Signals connected to DSO:
  - DDS RF signal
  - BuTiS T_0 pulse signal
  - DDS Trigger output

SCU – Scalable Control Unit
DSO – Digital Storage Oscilloscope
CEL – Calibration Electronic Module

Numerical optimization – Parameters to be optimized

- Motivation:
  - Minimize time needed for the calibration
  - Guarantee convergence

- Sine fit parameters:
  - Number of iterations for frequency grid search
  - Number of harmonics included in the fitting function

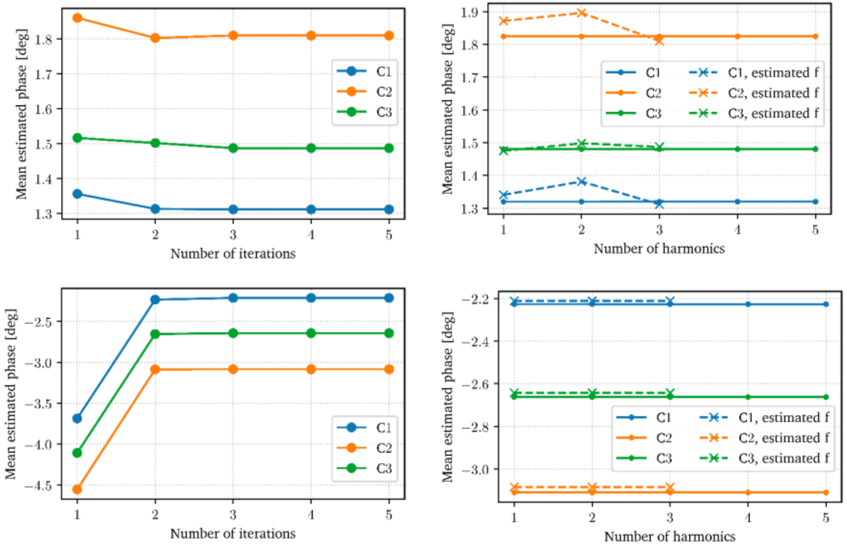
- Amount of data for sine fit
  - Number of sine waves per measurement trace
  - Number of samples per sine wave

Numerical optimization – Sine fit parameters

- Estimated phase converges after 3 iterations of the frequency grid search
- Estimated phase constant for 3PSF – first harmonic is sufficient
- Estimated phase improves with number of harmonics increased for 4PSF
- Difference between two approaches is below 0.1°

Number of iterations

Number of harmonics



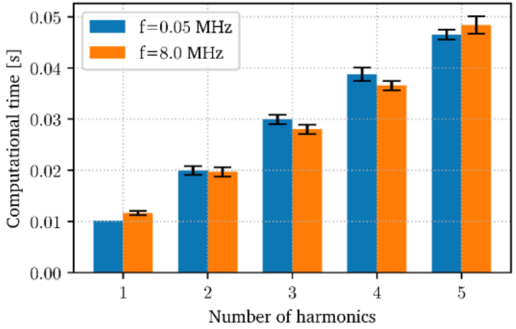
f: 0.05 MHz

f: 8 MHz

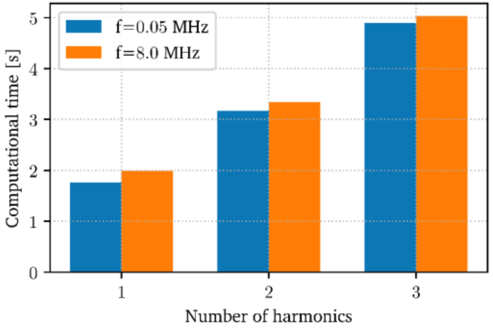
Processing time and choice of SFA

- Processing time increases with the number of harmonics for both methods
- Processing time is not a function of the frequency of the sampled signal
- 4PSF algorithm becomes impractical for harmonic numbers larger than 3
- Processing time: 3PSF is preferable to the 4PSF

3PSF



4PSF

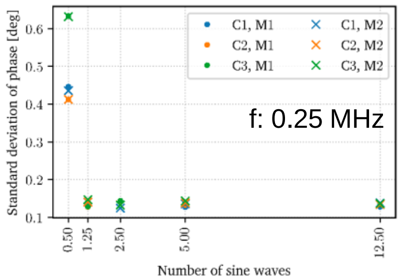


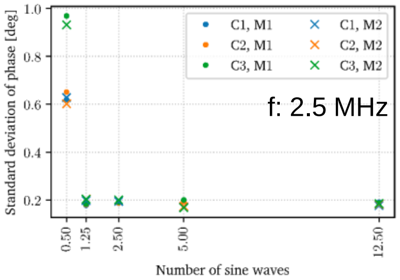
Number of harmonics	1	2	3	4	5
Average processing time, 3PSF	10.8 ms	19.9 ms	29 ms	37.7 ms	47.4 ms
Average processing time, 4PSF	1.9 s	3.3 s	4.9 s	-	-

Numerical optimization – Amount of data for sine fit

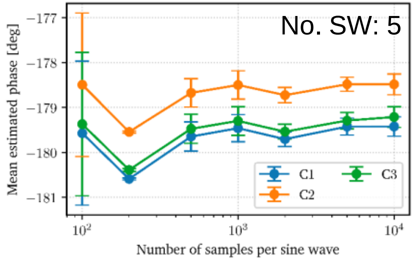
- 3PSF with one harmonic is used
- Constant standard deviation of phases if more than one RF period of the sine wave is sampled
- Possible to process data series with non-integer number of sine waves
- Calibration with an arbitrary frequency step
- Sufficient accuracy achieved with 2000 samples per sine wave
- Recommended measurement parameters obtained, maintained by a lookup table

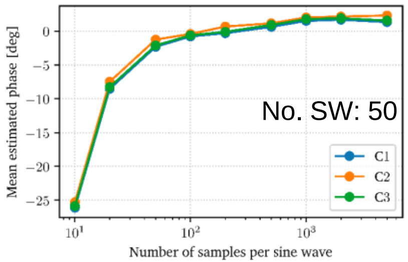
Number of sine waves





Number of sample per sine wave



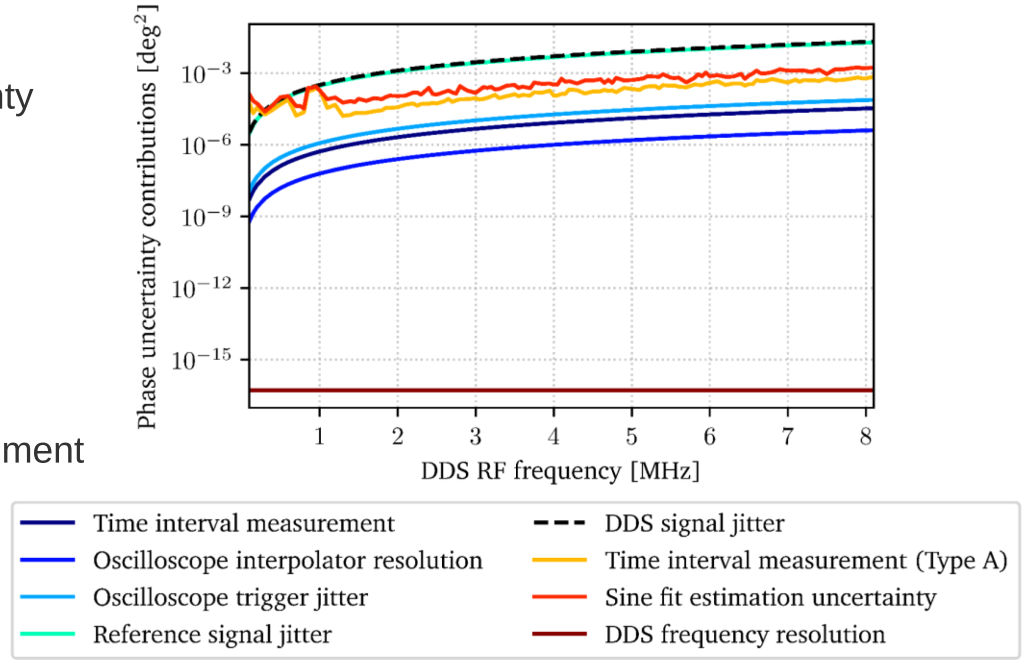


Uncertainty analysis

- Squared phase uncertainty contributions
  ➔ Combined phase measurement uncertainty
- Main uncertainty contributions:
  - DDS frequency resolution
  - Measurement instrument uncertainty
  - Sine fit estimation and oscilloscope time interval measurement (Type A evaluation)
  - Reference and DDS RF signals jitters

- Expanded uncertainty of the phase measurement (k=2, i.e. ~95% coverage probability) ≤ 0.5°

- To increase accuracy:
  - Jitters
  - DSO with better timebase accuracy and ADC resolution

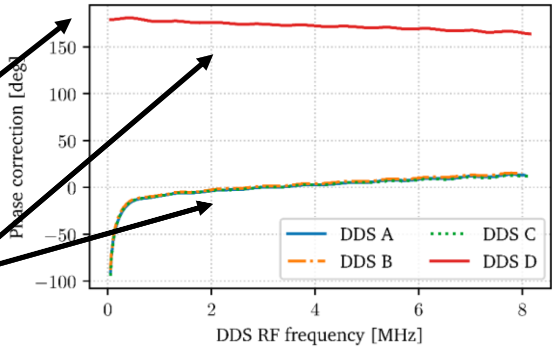


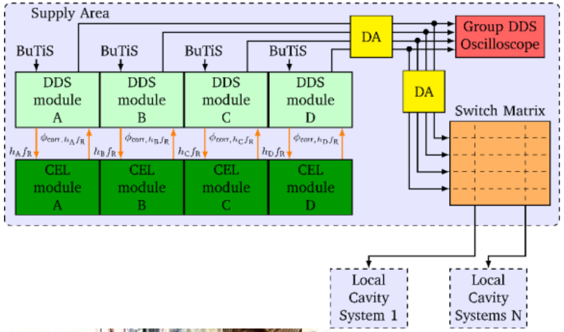
Application at GSI: SIS18 Group DDS calibration

- DA influence is also compensated

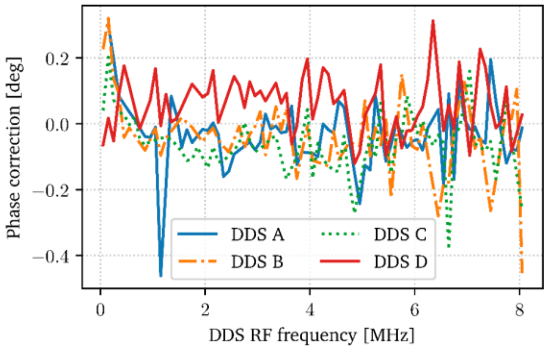
  Different HW revision

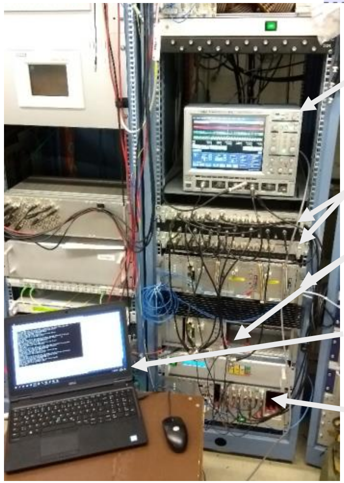
  Reflections due to Half-wavelength (λ/2) resonance





- Calibration time 12 minutes for one module





Group DDS Oscilloscope

DAs

CEL modules

Calibration PC

SCU and Group DDS modules

- Result is affected by the components after the calibration point
- Remaining phase error after the calibration is below ±0.5°

Phase calibration stability

- Potential influence sources:
  - Supply voltage variations ➔ Studied in detail
  - Ambient temperature variations ➔ Studied in detail
  - Variations in cooling conditions (due to e.g. atmospheric pressure or humidity change) ➔ Only seasonal changes; negligible
  - Degradation of components with time (aging) ➔ Prevented by periodic repetitive calibrations

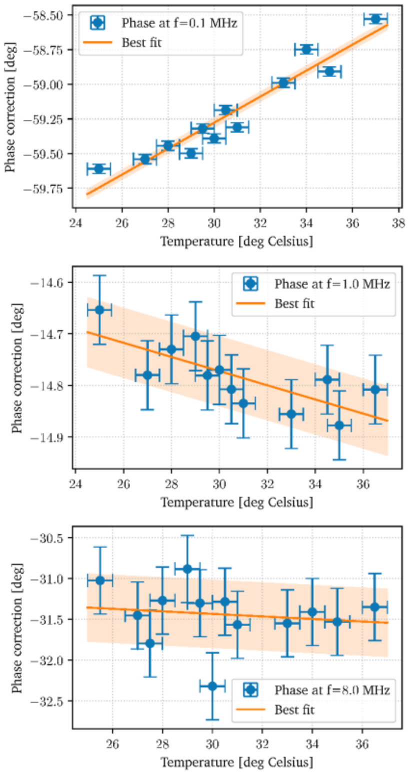
Room temperature influence

- Temperature sensor measures air temperature in the vicinity of Group DDS crate
- Forced air cooling of crate is used
- Phase calibration data measured at different levels of the ambient temperature (temperature variations 25-36 °C)
- Data grouped by frequency and temperature

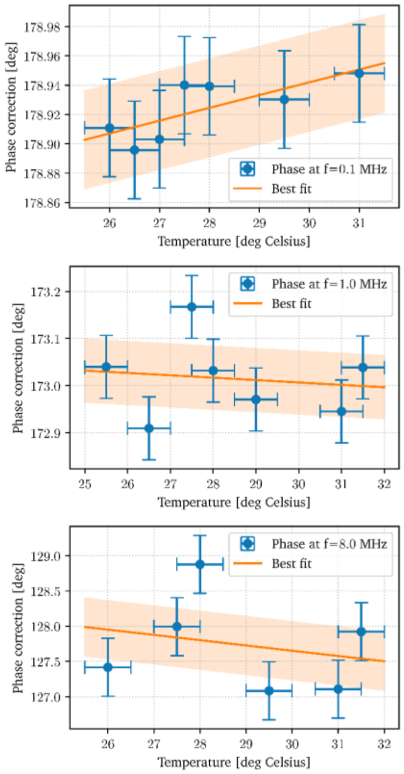
- 0.5° for each 5°C increase in temperature in the area where the calibration curve has the largest gradient
- Almost constant output phase for other regions

- Once per season calibration

DDS HW revision: 1.453



DDS HW revision: 2.26



Supply voltage influence

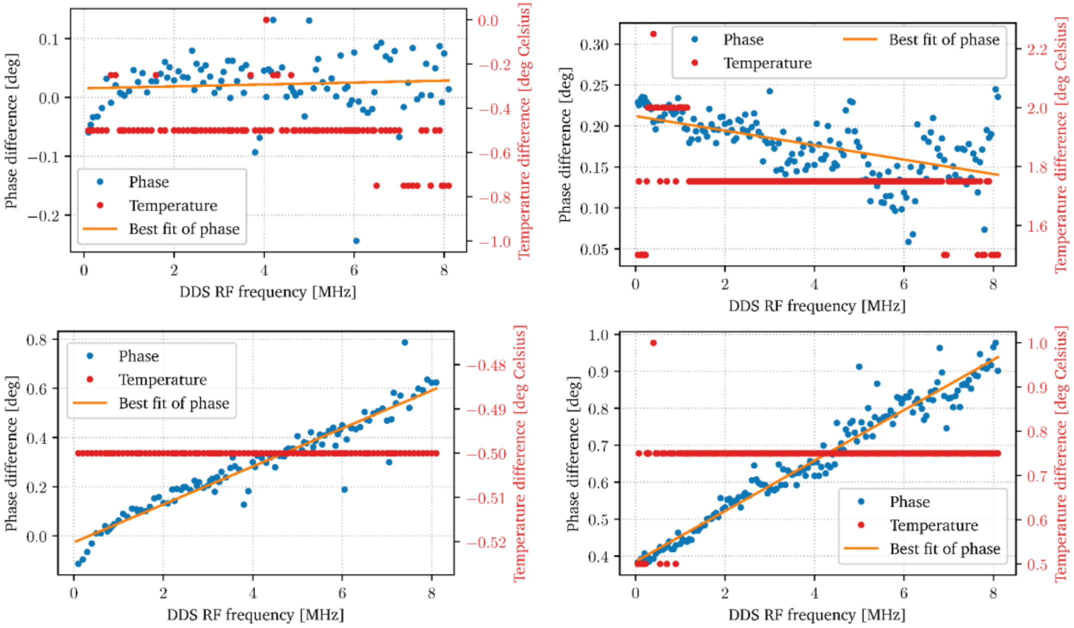
- Values measured at two different levels of the supply voltages
- Temperature variations never exceeded 2.5°C

- No influence of the analog supply voltage
- Linear increase of phase with the digital supply voltage
  - Phase deviation 0.6° @ 8 MHz for +0.5 V
  - Time delay measurements: timing of the resynchronization process

- Monitoring or stabilization of the supply voltages, accuracy better than 10%

DDS HW revision: 1.453

DDS HW revision: 2.26



Summary

- Phase calibration method based on SFA is developed
- An approach to obtain phase corrections with respect to the reference pulse train is demonstrated
- Measurement parameters are analyzed
- Recommended parameters for the application at FAIR are derived
- Measurement uncertainty analysis is performed, uncertainty contributions are identified
- Application at SIS18 is demonstrated
- Stability and environmental influences are analyzed

Acknowledgments

- Prof. Dr. Harald Klingbeil
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- Dr. Bernhard Zipfel
- Stefan Schäfer

- The department Ring RF systems

Backup: Uncertainty analysis I

- DSO interpolates trigger location
- Trigger time compensation term to obtain a correct phase of the DDS module:

$$\Delta\tau_\mathrm{t} = t_0 - t_\mathrm{t}$$

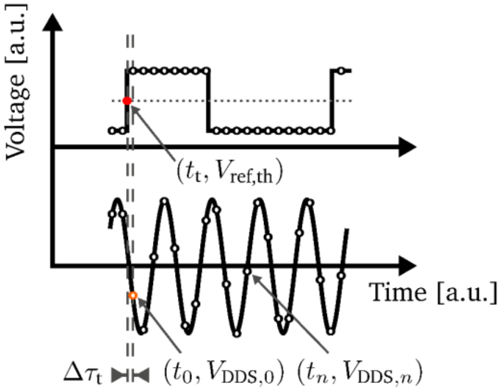
- Measurement model:

$$\phi_{\mathrm{e},f} = \phi_{\mathrm{meas},f} - 2\pi f_{\mathrm{DDS\ RF}} \left(N_\mathrm{ref} T_\mathrm{ref} - \tau_\delta + \Delta\tau_\mathrm{t}\right)$$

- Combined uncertainty of the measured phase correction:

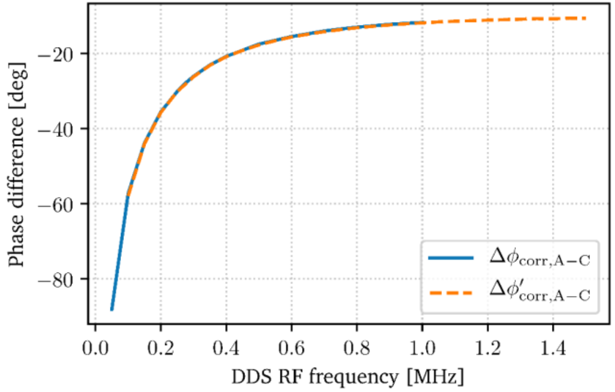
$$u_c(\phi_{\mathrm{e},f}) = \Big(u^2(\phi_{\mathrm{meas},f}) + (2\pi(\tau_\delta - N_\mathrm{ref}T_\mathrm{ref} - \Delta\tau_\mathrm{t}))^2 u_\mathrm{c}^2(f_{\mathrm{DDS\ RF}}) + (2\pi f_{\mathrm{DDS\ RF}})^2 u^2(\Delta\tau_\mathrm{t})\Big)^{1/2}$$

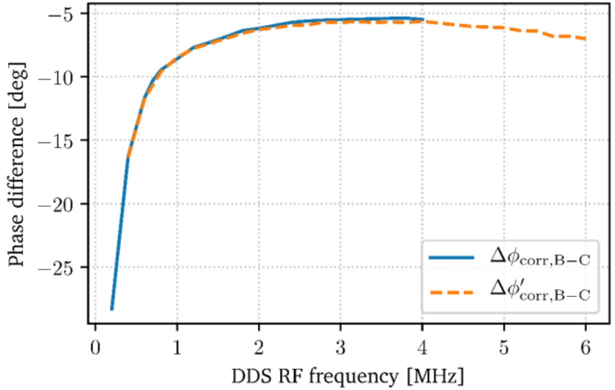
- Identified elemental uncertainties can be combined



Backup: Comparison with the formerly used calibration method

- 3 Group DDS modules operating at the harmonics 1, 4 and 8
- Phase calibration data measured with both methods





Backup: Machine Development Experiment

- The method was used during the beam time operation
- Phases estimated from recorded traces
- Phase difference in the scale of the fundamental
- Phase deviation between modules A and B increases during the acceleration by about 0.2°
- Phase deviations of modules are below 0.5°
- Successful realization of multiharmonic operation over the complete acceleration cycle